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A slack moored wave energy converter

by

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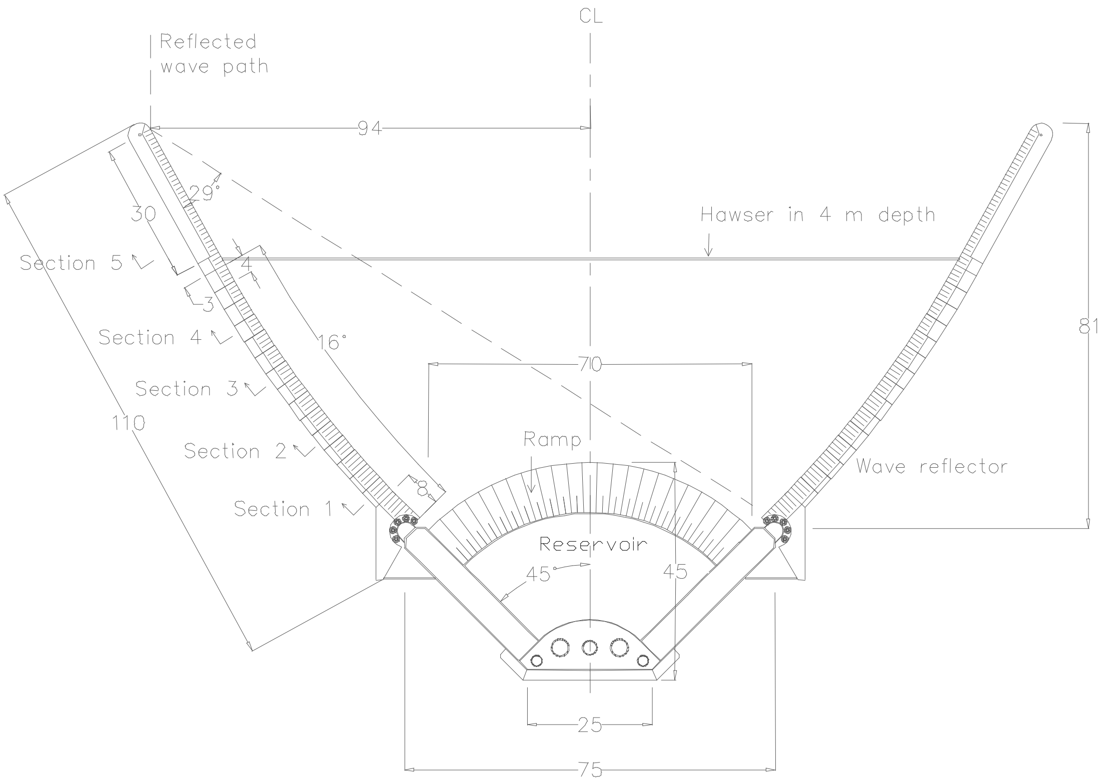

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Wave Dragon – A slack moored wave energy converter

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ABSTRACT

This paper concerns with the development of the wave energy converter (WEC) Wave Dragon. This WEC is based on the overtopping principle. An overview of the performed research done concerning the Wave Dragon over the past years is given, and the results of one of the more comprehensive studies, concerning a hydraulic evaluation and optimisation of the geometry of the Wave Dragon, is presented. Furthermore, the plans for the future development projects are sketched.

1. INTRODUCTION

Over the recent years wave energy has gradually been brought into focus, as it has become clear that the fossil energy resources are limited, and cause large environmental problems, e.g. CO_2 pollution. On this background a number of different wave energy converters have been proposed. The government in Denmark decided to appropriate approx. 2.7 mill. ECU to the development of wave energy devices over two years, 1998-1999. Among the wave energy concepts receiving financial support, is the Wave Dragon. The Wave Dragon is a floating wave energy converter of the overtopping type, developed by Erik Friis-Madsen from the Danish engineering company Löwenmark F.R.I..

2. DESCRIPTION OF THE WEC

The Wave Dragon WEC can briefly be described as consisting of three components (see Figure 1 and 2):

- A device for focusing the waves – the wave reflectors.
- A device for capturing wave crests in a low head reservoir.
- A number of low head turbines for converting the hydraulic head and flow into electricity

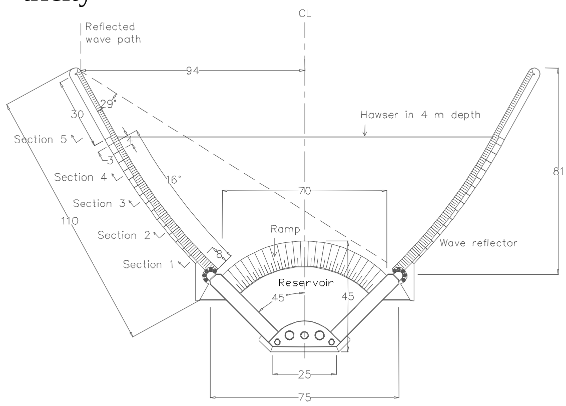

Figure 1: Plan view of the Wave Dragon. Measures are in m.

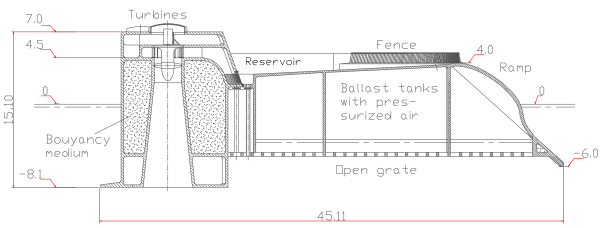

Figure 2: A cross section of the ramp and basin part of the Wave Dragon. Measures are in m.

The Wave Dragon is primarily constructed of reinforced concrete. The lifetime expectancy of the concrete part of the construction is at least 50 years, without major maintenance costs.

15 equal straight elements constitute the main part of each of the two wave reflectors. In addition a longer element with less draught is attached at the end. Transition elements are connecting the reservoir and the main part as well as the main and the ending part of the wave reflectors.

Curvature of the wave reflectors is obtained by having an angle between the elements. Thus in the following the curvature is described by these angles. For the design proposed by the developer the curvature is constantly 1,0°.

The cross sections marked in Figure 1 are shown in Figure 3. The lower parts of the reflectors are made of reinforced concrete, while the upper parts are made of a steel shell.

The bottom of the platform is an open grate allowing water to enter the body. The draught is thus adjusted by a pressurized air system. The Wave Dragon is designed to float even though the ballast tanks are filled with water.

The Wave Dragon will presumably be gravity anchored, however, other systems such as pile foundation or suction anchors are under consideration. A number of hawsers are fastened to the wave reflectors and the reservoir and joined at a buoy, which is connected to an anchoring system at the sea bottom.

The Wave Dragon is based upon technique presently known and available at industrial standard. Certain parts of Wave Dragon are technically innovative to such a degree that a patent is expected.

The weight of the reservoir part of the Wave Dragon is roughly calculated to 6.000 tons, and the weight of each reflector is approximately 2.000 tons. Thus, including 1.000 tons of water in the basin, the total weight is 11.000 tons.

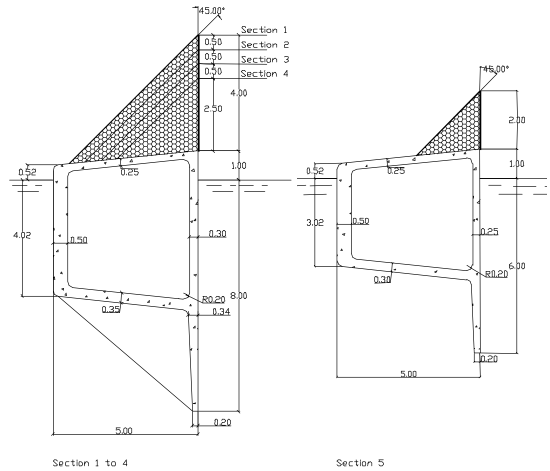

Figure 3: Cross sections 1 to 5 of the wave reflectors shown in Figure 1. All measures are in m.

In the development of the Wave Dragon the goal is to produce 3 MW per unit in 4-m waves. The offshore floating platform will be placed typical at 20 to 50 meters water depth, which in the Danish part of the North Sea is equivalent to 25 - 100 km from the coastline. The cost of transmission of the power to the coast forces the developer of the Wave Dragon to think in large-scale power production. A typical wave energy power plant of the Wave Dragon type will consist of 200 units of each 3 MW as a mean value (max. power of 4 MW).

3. RESEARCH PERFORM UNTIL NOW

Until now several researchers have investigated various topics related to the development of the Wave Dragon. Examples are studies of the flow from the basin through the turbines, see (1), and a feasibility study (4). This feasibility study was funded by the EU Commission and has shown that the expected price of electricity produced by the Wave Dragon of the development stage of today to be 0.07 - 0.11 ECU/kWh.

Furthermore, a hydraulic evaluation and a preliminary geometrical optimization of the two main parts of the Wave Dragon, namely the wave reflectors and the overtopping ramp have been carried out at Aalborg University, see (3).

4. HYDRAULIC EVALUATTION OF THE GEOMETRY

4.1 Conditions of the analysis

The investigations at Aalborg University are described in the following. This analysis have been related to a 1:3 scale test version of the prototype, for placement in the Nissum Bredning in the northern part of Denmark (see Figure 4). Here the wave climate is less aggressive than out at the intended position of the prototype in the North Sea, and was therefore considered suitable for a test site.

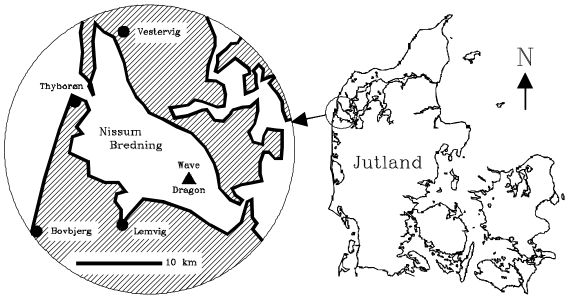

Figure 4: Position of the investigated version of the Wave Dragon.

At the selected location the wave climate have been found by an analysis of wind data from 3 locations around Nissum Bredning. As the Wave Dragon always will sway towards the waves, seastates from all wind directions can all be combined. On the basis of this wind / fetch analysis 7 wave conditions have been defined, see Table 1.

Table 1: Wave conditions in Nissum Bredning.

Wave situation	H_S [m]	T_P [s]	Occur. prob. [%]
0	<0.2	<2.0	30
1	0.2	2.0	24
2	0.4	2.5	30
3	0.8	3.0	11
4	1.2	3.5	3
5	1.5	4.0	2
6	>1.5	>4.0	Approx. 0

In the optimization and evaluation of the Wave Dragon only wave situation 1 through 5 have been considered, as the contents of wave energy in situation 0 negligible. Situation 6 is considered a storm condition, under which the Wave Dragon will not be producing electricity.

4.2 Optimization of the reflector layout

It was chosen to perform the optimization of the shape of the reflectors in the plan by use of a 2-D depth integrated numerical wave propagation model, based on the Mild Slope equation. The reflectors that are not extending to the bottom cf. Figure 3 was modeled by letting the reflectors in the numerical model absorb the amount of energy corresponding to the amount that passes under the reflectors. Furthermore, by using the numerical model it is assumed that the structure is fixed. Superficial calculations of the movements of the Wave Dragon supported this assumption.

Using this numerical model it was possible to evaluate different reflector shapes in terms of how much the significant wave height H_S, in the area where the ramp is placed, is increased, compared to the H_S given in front of the reflectors. By running a large number of numerical calculations, with different reflector shapes, it was found that the highest H_S-ratios was obtained by using a constant angle of 1.2° between each of the 16 elements of the reflectors, and a starting angle of 45°.

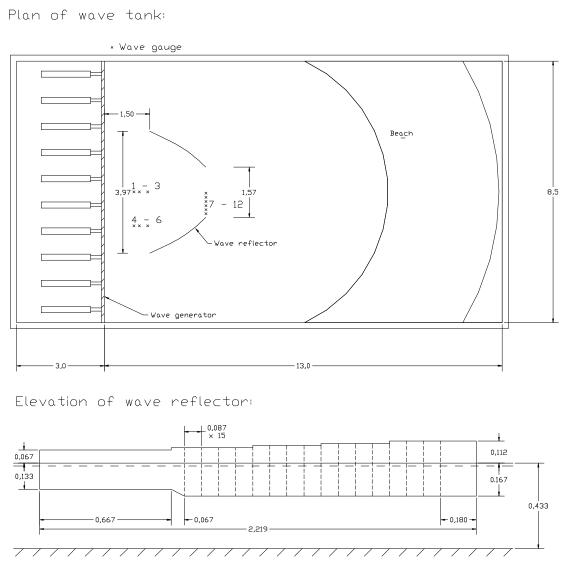

Figure 5: Model layout of the laboratory tests.

The selected reflector shape was then tested in a wave tank, using a model in a 1:15 length scale to the Nissum Bredning model (equal to 1:45 to the prototype), see Figure 5. This resulted in H_S-ratios in good agreement with the results found from the numerical calculations.

Table 2: Wave height ratios based on the numerical and experimental evaluation of the reflectors.

Wave situation	H_S-ratio, numerical	H_S-ratio, experimental
1	1.92	1.71
2	1.57	1.56
3	1.36	1.42
4	1.36	1.39
5	1.32	1.33

Applying these wave height ratios to the wave heights given in Table 1 results in the focused wave heights as shown in Figure 6.

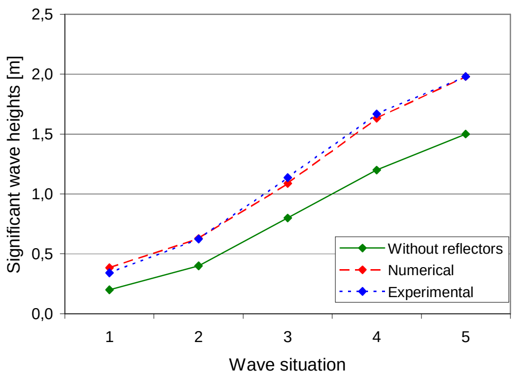

Figure 6: The wave height ratios and significant wave heights corresponding to the 5 wave situation found in the numerical analysis and the laboratory tests.

From Table 2 it is seen that the reflectors increase the wave height with a factor of ~1.5 in average. As the amount of the energy in the waves increase with the square of the wave height, the reflectors thus have doubled the available amount of energy at the ramp. As the reflectors increase the total weight of the structure with approximately 60 % of the ramp/reservoir part alone (and the price of the structure is assumed to be proportional with the weight), it is seen that the reflectors contributes positively to the overall economy of the Wave Dragon.

4.3 Overtopping of different ramp profiles

After the waves are focused by the reflectors they will overtop the ramp and enter the basin. It is therefore essential that the ramp allow as much overtopping to the highest possible level, which also imply that wave breaking on the ramp should be avoided. This is contrary to what is normally the target when designing slopes in connection with other marine constructions, e.g. breakwaters, where the overtopping is reduced as much as possible. Thus, there is practically no experience with designing slopes with this aim, and an experimental parametric study was therefore performed to find the optimal ramp layout. Generally speaking, parameters like the cross section shape, curvature in the plan, draught and crest freeboard is important parameters, but in the performed model tests the emphasis was on the influence of change of the cross section shape and the crest freeboard.

In order to investigate whether it was possible to increase the overtopping, tests were performed using different slope angles and curvatures of the ramp profile.

In the study of overtopping of the ramp, different overtopping formulas found by dimensional analysis were fitted to the laboratory data. Best result was obtained by using a formula on the form:

$$\frac{q}{\sqrt{gH_S^3}} = a \cdot e^{\left(-b \cdot \frac{R_C}{H_S}\right)} \qquad 1$$

where q is the average flow (overtopping) [m^3/s/m], R_c is the crest freeboard and g is the gravity acceleration. a and b are fitting coefficients. This formula has also been used for describing overtopping of breakwaters (5).

From formula eqn.1 an expression for the obtained potential energy in the basin is established, by multiplying with the crest freeboard. Taking movements of the basin part and wave overtopping volume distribution into consideration, a new parameter is introduced namely the rim height r, defined as the height from the MWL in the basin to the crest freeboard:

$$\begin{aligned} E_{pot} &= q \cdot (R_c - r) \cdot g\rho_w \\ &= a \cdot \sqrt{gH_s^3} \cdot (R_c - r) \\ &\quad \cdot g\rho_w \cdot \exp\left(-\tfrac{b}{H_s} \cdot R_c\right) \end{aligned} \qquad 2$$

where ρ_w is the density of the water.

In the following calculations the MWL in the basin is set 0.10 m below the ramp crest freeboard, i.e. a rim height of 0.10 m (~0.30 m in the North Sea scale).

Eqn.1 gives the overtopping discharge as a function of the wave height and the crest freeboard. It is generally accepted (and also seen during the present investigation) that the overtopping furthermore is a function of the wave period.

The reason for neglecting the wave period in the equation is that for a given location it will be reasonable to express the wave period through the wave height and a proportionality coefficient *c*:

$$T_p = c\sqrt{\frac{H_s}{g}} \qquad 3$$

In Nissum Bredning the waves are fetch limited with a calculated proportional coefficient *c* in the range 8 – 10, whereas fully developed seas, like the North Sea, have coefficients up to 17.

Table 3: Overtopping coefficients in eqn.1 for the 5 wave situations in Nissum Bredning.

Wave situation	*c* coefficient	*a* coefficient	*b* coefficient
1 & 2	10,2	0,078	2,11
3, 4 & 5	8,7	0,043	1,66

Table 3 gives the fitted overtopping coefficients *a* and *b* for the used wave situations. It is seen that the waves in the largest wave situations are pronounced fetch limited.

Because of the dependency of the relation between H_s and T_p the overtopping discharges can only be scaled to other locations having different proportional coefficients with care.

On the background of the tests with the different shapes the following were concluded:

- The slope angle has been investigated for angles between 35 and 60° as it is assumed that the slope must be relatively steep to prevent wave breaking on the ramp. Slope angles between 35° and 50° do not affect the overtopping significantly, but higher values will decrease it. A slope of 60° only gives about 70 – 80 % of the overtopping of a slope of 40°.
- The influence of a ramp profile with curvature has been tested by using 4 different profiles. The tests showed that the investigated profiles did not have significant differences with respect to overtopping.

On this background it seems reasonable to use the reference ramp profile in the further tests in the wave tank.

4.4 Calculated overall efficiency

From the analyses of the ramp profile the obtained potential energy as a function of the crest freeboard is found by eqn.2. This is presented in Figure 7 for the 5 wave situations weighed with the probability of occurrence.

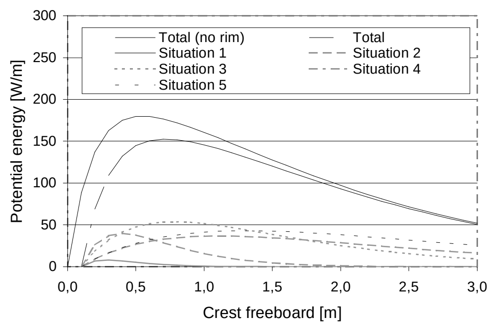

Figure 7: Potential energy obtained in the basin per time and width unit as a function of the crest freeboard. Curves are calculated using the data from the 5 wave situations (after focusing by the wave reflectors) weighed with the time of occurrence. "Total" is the sum of the 5 situations, while "Total (no rim)" curve is the energy calculated with rim height r = 0.

From this figure the optimal crest freeboard in each wave situation can found, by seeking the highest amount of potential energy for each wave situation and noting the corresponding crest freeboard. This results in the optimal crest freeboards given in Table 4. With the wave parameters in Table 1 the obtained potential energy weighed with the probability of occurrence is found for the optimal crest freeboard in each wave situation.

Table 4: Optimal crest freeboard with corresponding obtained potential energy weighed with time of occurrence for the 5 wave situations.

Wave situation	Crest freeboard [m]	Potential energy [W/m]	Contribution to total [%]	Occur. prob. [%]
1	0.28	8	4	24
2	0.40	40	22	30
3	0.78	53	29	11
4	1.11	37	20	3
5	1.31	43	24	2
Sum	-	180	100	70

From Table 4 it is seen that the Wave Dragon in the Nissum Bredning scale in mean capture 180 W per m. of the ramp in 70 % of the time. As the width of the ramp is 23.6 m, the Wave Dragon as a mean over all time will capture 3.0 kW. Comparing this to the amount of energy that passes the opening between the reflectors, which is approximately 21 kW (corresponding to 0.35 kW/m), shows that the efficiency is 14 %. Thus, the amount of captured energy in the reservoir over one year is approx. 26 MWh for the Wave Dragon in the Nissum Bredning scale. Scaling this directly to by 1:3 to the North Sea results in a yearly amount of captured energy of 1.3 GWh.

Though, taking into account that the North Sea waves have relatively longer periods than waves in fjords like Nissum Bredning because they are not fetch limited, will result in a significantly higher energy production. Such a consideration results in an estimated yearly amount of captured energy of 5.7 GWh corresponding to an average efficiency of 15 %.

4.5 Tests of the combined system

In order to check the performed calculations model tests with a model of the complete Wave Dragon (reflectors, ramp and reservoir) were performed in the wave tank. In these tests as well as the others, the structure were fixed, and furthermore the crest freeboard was fixed at 0.033 m (~0.50 m in the Nissum Bredning prototype). In small waves (wave situation 1 and 2) the freeboard was higher than what was found to be the optimal crest freeboard in these wave situations. In high waves (wave situation 3, 4 and 5), were the used crest freeboard corresponded better to the optimal crest freeboard, the obtained potential energy corresponded fairly well with the prediction, even though it was found to exceed the predicted values significantly for the highest waves.

From these model tests an average amount of captured energy was found to be 12 % of the energy passing the opening between the reflectors. This result is, as expected, slightly lower than the corresponding value found in the calculations where the crest freeboard was adjusted to the optimal for each wave situation.

Adjusting the crest freeboard to actual wave situations is seen to improve the performance of the Wave Dragon.

5. CONCLUSION

From the numerical calculations and performed model tests based on the Wave Dragon in the Nissum Bredning scale, it has been seen that the amount of potential energy obtained in the reservoir is in the range of 12 – 14 % of the wave energy passing the opening between the reflectors. The tests of the combined system also verified the results of the numerical calculations of the focused wave field and the overtopping formula.

Furthermore, the model tests and the calculations showed that altering the design on certain points could increase the efficiency. On this background the layout of the Wave Dragon has been updated before the further investigations. Thus, the height of the reflectors has been increased, as overtopping of these were observed during the model tests, the draught has been increased by 33 % and the geometry in the plane of the ramp and the reflectors has been slightly altered.

6. FUTURE DEVELOPMENT

After the referred study new test programmes have been initiated and is ongoing at the time being.

6.1 Danish test programme

The Wave Dragon will be tested in the coming months financed by the Danish Energy

Agency. The Danish test program will establish data for the following, using a floating model of the Wave Dragon:

- Average water flow in the reservoir.
- Forces in the reflectors.
- Mooring forces
- Movements of the floating structure at sea.

These results will bring the development a major step further. The basic, preliminary data will be available October/November 1998. The tests are carried out at Aalborg University using a model in scale 1:50 that are being build at the Danish Maritime Institute.

6.2 EU test programme

Offshore WEC's, including the Wave Dragon, can only store a limited amount of energy. Most of the known designs of WEC's have practically no energy storage capacity at all. The energy of the water reaching the turbines is thus fluctuating with the same period as the waves - typical 5 - 15 s. Further more waves normally travel in groups. The period of the variations in power level caused by this phenomenon is often 1 minute. Consequently the turbines in all off shore WEC's must be regulated with automatic and very fast control equipment. Also valves and wicket gates etc. in the turbines must be able to react quickly. The Wave Dragon has a relatively large storage capacity (1,500 m^3 equivalent to about 3 times the wave period or 50 MJ), but even the Wave Dragon can not flatten out the variations in power caused by the wave groups.

On this background a more detailed test program dealing with the optimisation of the hydro turbines to be used in the Wave Dragon is planned, and the Danish test programme will form the basis of these tests.

The participants in this development consists of manufactures of hydro turbines, a developer of generators, research institutes in Germany, UK, Ireland, Denmark and Sweden.

This test program is the next phase of the necessary development before a prototype in scale 1:3 or 1:1 can be tested. The programme will be initiated in October/November 1998.

The objectives of the proposed EU test programme are to establish:

- A reliable set of inflow data (real time and not only average) to the reservoir based on wave data from the North Sea.
- A strategy for the choice and regulation of turbines.
- A strategy for the choice of hard- and software needed to regulate and control a set of turbines.
- A strategy for the development of a system for optimal control of the crest freeboard.
- A strategy for the power generation and transmission to the sea shore.
- A basis for design of a prototype of Wave Dragon suitable for offshore conditions.
- An updated feasibility study.

The methodology is to perform tests on:

- A model in scale 1:50 in a wave basin simulating 3-D North Sea conditions.
- A model in scale 1:10 of a cross section of the reservoir equipped with a model of a turbine. This test will be performed in a large wave tank with 2-D waves with facilities to simulate the working conditions of Wave Dragon in 5 m high waves.

This EU test programme is expected to be concluded ultimo year 2000.

7. ACKNOWLEDGEMENTS

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